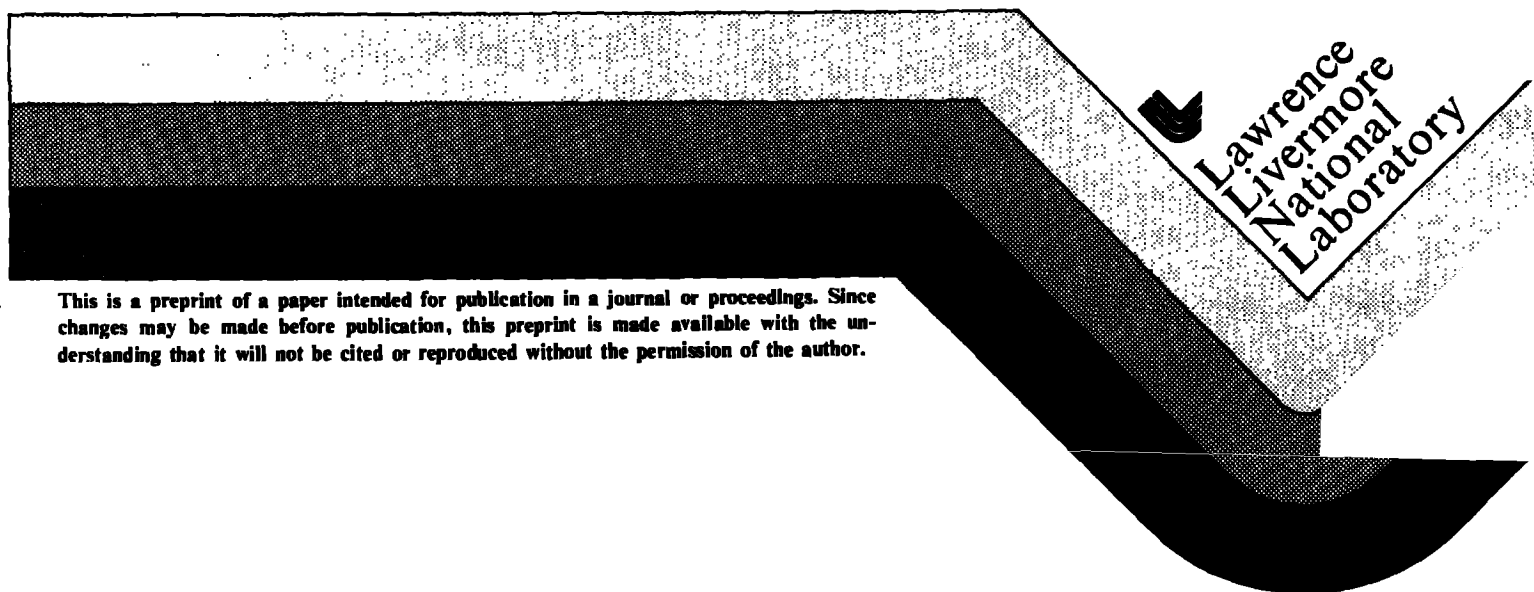


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MINIMARS, A 600-MWe ADVANCED MIRROR-FUSION REACTOR DESIGN*

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ABSTRACT

MINIMARS is a conceptual fusion reactor based on tandem-mirror magnetic confinement. It is designed to produce 600 MW net electric for 41 mils/kWh and to be capable of passive shutdown and afterheat removal.

INTRODUCTION

MINIMARS is the latest in a series of tandem-mirror fusion-reactor studies done to assess the commercial potential of the tandem-mirror magnetic-confinement concept.

The objective of the MINIMARS study was to develop a conceptual design that: (1) is of modest size, 600 MWe; (2) is economically competitive, <50 mils/kWh; (3) is passively (i.e., inherently) safe in terms of plant financial investment, as well as public safety.

The Mirror Advanced Reactor (MARS) (Ref. 1), the forerunner of MINIMARS, was characterized by a quadrupole, end-cell, magnetic configuration in the form of a complex, double yin-yang set. In MINIMARS, we retain the features of potential plugging of passing central-cell ions, together with the thermal barrier, but obtain MHD stabilization by a new end-cell concept comprising a compact octopole magnet and a mirror-confined hot electron mantle. The octopole plug has several advantages over the quadrupole (MARS-type) plug, including a considerable reduction in the end-cell magnet weight and cost, and enables central-cell ignition to be achieved with much shorter central-cell lengths.

The MINIMARS study was done during 1985-1986 by Lawrence Livermore National Laboratory in partnership with the Fusion Engineering Design Center, the University of Wisconsin, TRW, Grumman Aerospace Corporation, General Dynamics/Convair, Argonne National Laboratory, and the Canadian Fusion Fuels Technology Project. The MINIMARS reactor is expressly designed for a short (~4 to 5 years) construction time by specifying factory-built modules and a passively safe blanket and thermal cycle. In this way, we intend to achieve a small reactor based on the tandem-mirror principle,

which will minimize the utility's financial risk, thereby providing an attractive alternative to the more conventional, large, fusion plant designs encountered to date.

Since its inception in 1976, the tandem-mirror concept (Refs. 2,3) has motivated experiments (Refs. 4-6) and reactor studies (Refs. 1,7,8) because a tandem-mirror reactor is expected to exhibit the following attractive features:

- Steady-state operation (no pulsed loads or cycling fatigue).
- Linear geometry with power produced in relatively simple central cell.
- Low charged-particle heat fluxes to the first wall ($<10 \text{ W/cm}^2$).
- No required driven current and no identifiable plasma disruptions.
- Open magnetic geometry accommodating direct electrical conversion of charged-particle power.
- Natural impurity diversion via plasma halos.
- High-beta operation as a result of the machine's linear geometry.

KEY FEATURES OF MINIMARS

The MINIMARS reactor (Fig. 1) has an 88-m-long cylindrical central cell producing 1230 MW of D-T fusion power in steady state. Electrostatic potentials created in the thermal barrier plugs, as in MARS (Ref. 1), confine the central cell ions in the axial directions. Residual radial losses of central cell ions are sustained by pellet injection and alpha particle heating (ignition) in the central cell. Approximately 38 MW of continuous electron-cyclotron-heating (ECH) and neutral beams in the thermal barrier plugs is required to maintain axial confinement and MHD stability. The MHD stability derives from the minimum $|B|$ principle as in MARS, but the minimum $|B|$ fields in MINIMARS are created in a hot electron annulus (mantle) around the thermal-barrier plasma core by means of higher-order octopole coils rather than by quadrupole (yin-yang) coils as in the case of MARS. The result is much more compact, lower-mass, and lower-cost plugs for MINIMARS, as evident in Fig. 2. The smaller plugs in MINIMARS in

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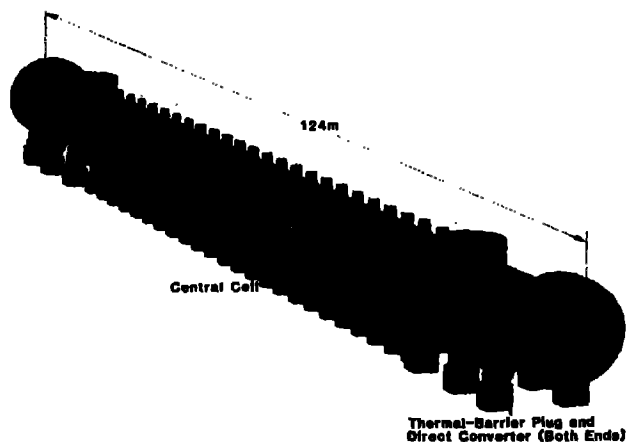


Fig. 1. MINIMARS 600 MWe tandem mirror reactor.

turn allow smaller central cells and power output to be economical.

Table 1 compares principal parameters and key features of MINIMARS and MARS. Ordinarily, one might expect reduced plant efficiency and higher COE for smaller plants due to economy-of-scale effects. This is more than offset in MINIMARS through the improved octopole plug configuration, which results in both higher Q and higher central-cell beta (lower central-cell magnetic fields). Thus, although MINIMARS produces only half the electricity compared to MARS, the plant efficiency is preserved at 36%, and the levelized COE is reduced ~10% in constant dollars. A major contributor to the

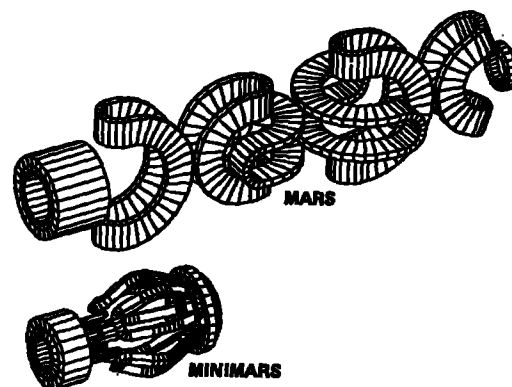


Fig. 2. Comparison of the end-cell magnetic configurations for the Mirror Advanced Reactor Study (MARS) and MINIMARS.

improvement in MINIMARS economics derives from relatively reduced magnet mass both in the plug coils and central cell coils.

MINIMARS ACCOMPLISHMENTS

We have developed a single reference-point design for MINIMARS in sufficient detail to make a first level cost and safety assessment. The information we have generated in this design supports our conclusion that the MINIMARS cost and safety objectives can be met, and the key findings of this study are highlighted here.

The bottom line COE estimate of 41.4 mills/kWehr meets our objective of <50

Table 1. Principal parameters and features of the MARS and MINIMARS tandem mirror reactors.

| Type of plugs | MARS quadrupole/ thermal barrier | MINIMARS octopole/ thermal barrier |
|--|--|--|
| Net Electric Power (MWe) | 1200 | 600 |
| Steady State Fusion Power (MW) | 2600 | 1231 |
| Q Fusion Power/Heating Power | 26 | 32 |
| Neutron Wall Loading (MW/m ²) | 4.3 | 3.3 |
| Total Capital Cost ^a (M\$) | 3210 | 1644 |
| Cost of Electricity ^{a,b} (mills/kWh) | 46 | 41 |
| Mass-Power-Density (kWe net/tonne) | 44 | 100 |
| Reactor Length (m) | 211 | 124 |
| Central Cell Length (m) | 135 | 88 |
| Central Cell Magnetic Field (T) | 4.7 | 3.1 |
| Average Central Cell Beta (%) | 28 | 60 |
| Blanket Coolant/Breeder/ Multiplier/Structure | Pb83/L117 Pb83L117/HT-9 | He/Pb83L117 Be/HT-9 |
| Blanket Energy Multiplication | 1.39 | 1.46 |
| Coolant Outlet Temp. (°C) | 500 | 575 |
| Max. Blanket Temp. under LOCA/LOFA/LOSP ^c (°C) | 1000 | 600 |
| Shutdown Mode under LOCA/LOFA/LOSP ^c (°C) | Active | Passive |

^a1985 dollars.

^bConstant - \$, no inflation or escalation.

^cLOCA/LOFA/LOSP = Loss of coolant/loss of flow/loss of site power.

mills/kWehr. This cost estimate was made for a tenth-of-a-kind commercial plant, with appropriate accounting for passive-safety (non-nuclear grade construction), which represents about 25% lower COE than if MINIMARS were not passively-safe. This result is encouraging, in that this MINIMARS COE is competitive with many quoted future improved LWR designs. However, one must keep in mind the uncertainties in this MINIMARS design relative to fission-plant designs.

Fig. 3 shows the variation of COE and mass power density as a function of MINIMARS plant size (P_{net}), predicted by the tandem-mirror-systems code using costing algorithms for various subsystems normalized to the MINIMARS point design at 600 MWe. As expected for fusion plants in general, COE for MINIMARS vs P_{net} exhibits a fairly strong economy of scale. This is due partly to an increase in optimum wall loading with P_{net} (from 2 MW/m² at 250 MWe size, to 8 MW/m² at 2400 MWe size) and partly to a unique feature of tandem mirrors, namely, that fixed plug costs make a diminishing contribution to the total reactor cost as the central cell gets longer, as it does with increasing P_{net} . The direct capital cost scales nearly as an offset linear function of P_{net} .

An important consideration in the MINIMARS blanket design is meeting the objectives of passive shutdown and afterheat cooling in the event of a loss of cooling accident (LOCA).

Within a few seconds of LOCA, fusible plugs at selected first-wall locations would melt at a temperature slightly higher than the normal first-wall operating temperature, discharging small helium reservoirs built into the central cell, resulting in a cooling of the plasma and cessation of the fusion reaction in a few additional seconds (Ref. 10).

Subsequent to the plasma shutdown, afterheat from the decay of blanket

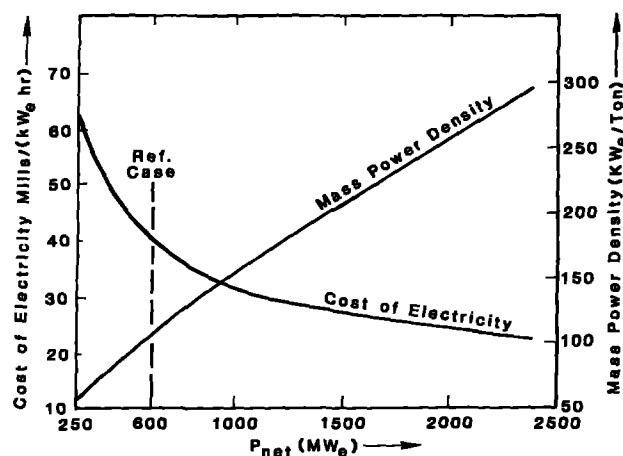


Fig. 3. MINIMARS economy of scale.

radionuclides radiates from the blanket to the reflector, and from the reflector to the shields by thermal radiation, assuming the gaps have an emissivity of 0.8, as would be acceptable for appropriately oxidized metal surfaces. Finally, the shields are passively cooled by H₂O heat pipes, which transfer the afterheat² to the reactor vault air. The blanket reaches a maximum temperature of about 600°C some 36 hours after shutdown, and then slowly cools off. This temperature rise probably would cause no blanket damage, and reactor operation could be restored as soon as the cause of the LOCA was corrected.

Besides protecting the plant investment (an important Three-Mile-Island issue), limiting the maximum temperature excursion in a LOCA also helps minimize the release of radioactivity in accidents. The reference case MINIMARS blanket holds only 1 gram of tritium in the Pb83Li17 breeder and He coolant, and other mobile tritium in the reactor vault (<20 grams) is estimated to cause less than 1 rem dose at the site boundary in an accident, even assuming no containment building. Also, this blanket contains no highly flammable materials.

FUTURE DIRECTIONS

At this time the main uncertainty regarding the attractiveness of this type of MINIMARS reactor (i.e., based on the concept of tandem mirrors with thermal-barrier plugs) is the issue of confinement scaling with density, electron temperature, and potential. A recent peer review (Ref. 11) of the tandem-mirror experimental program has judged sufficient progress in the experimental research to recommend continued experiments. The primary experimental issues concerning effects of ECH heating on hot electron losses, radial transport in the central cell, and gas charge exchange, would be estimated to scale to insignificance in the MINIMARS reactor regime. Nonetheless, MINIMARS requires confinement time, density, electron temperature, and potential roughly 100 times greater than those presently achieved, and such large extrapolations of present parameters necessitate further experimental progress before a MINIMARS reactor performance can be predicted with confidence. Of course, other advanced fusion concepts competing for small reactor applications, such as the Tokamak with second-stability, and the Reversed-Field-Pinch with F-8 pumping for steady-state current drive, are likewise not yet demonstrated experimentally and have substantial uncertainty in confinement scaling. Until any of these concepts is proven out, MINIMARS should remain a strong candidate for small fusion reactors.

In addition to improving the experimental data base in confinement, future work should also continue to seek ways to further simplify the design of the plugs. As part of

the MINIMARS study, we briefly surveyed many candidate ideas for simpler and cheaper plugs, compared to the reference case with octopoles and hot electron mantles, and we speculate that significant additional cost reductions are possible.

Finally, the University of Wisconsin group has recently proposed a tandem-mirror reactor burning deuterium and helium-3 fuel from lunar soil sources. This concept, called Ra (Ref. 12), promptly harvests the 14 MeV proton energy by non-adiabatically scattering the protons into the direct converter before they thermalize, resulting in unprecedented plant efficiencies of 60%. Perhaps this advanced fuel scheme would make best use of the most unique feature of the tandem mirror: an open field line geometry amenable to electrostatic direct conversion of charged-particle energy.

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